ANALYSIS OF HYDRODYNAMIC JOURNAL BEARING FOR HIGH SPEED SHAFT OF WIND TURBINE GEARBOX

A

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By

Pravez Khan

(Enroll. No. - 200160090101)

Under the Supervision of

Prof. H.C. Garg

Department of Mechanical Engineering

Guru Jambheshwar University of Science & Technology

Hisar-125001 (Haryana), India

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1. Introduction

The global energy requirements are increasing with the continuous growth of human population. A number of power generation techniques have been developed to fulfill this ever-increasing energy demand. Conventional power generation has two major limitations i.e. limited fuel reserves and pollution, which is forcing the researcher community to focus on renewable energy technologies. According to the International Renewable Energy Agency (IRENA), world's total renewable energy production has increased by 10.27% in 2021 as compared to last year (2799 GW) out of which wind energy secure second rank with rapid growth by 17.8% (733 GW) at the end of 2020 (IRENA, 2021). The wind turbine is a major component in wind energy system that has been changing so quickly in size and design due to continuous developments which may vary from onshore (land-based) to offshore. The Global Wind Energy Council (GWEC) predicted the new wind turbine capacity over 469 GW till the end of 2025 (IEA, 2021).

The global wind energy sector has grown rapidly among all the renewable energy resources in the last few years. However, wind turbine is still facing the problem of premature failure which directly influences the Maintenance, Reliability and Operating (MRO) cost. Electrical and electronic components are least reliable elements of the turbine and have the highest failure rate but in contrast the downtime is highest of about a week in case of gearbox and generator as shown in Figure 1. Eelectrical components are inexpensive and easy to restore or replace because of smaller size. On the other hand, heavy masses of main shaft, yaw, pitch, and gearboxes systems requires dedicated and expensive equipment for maintenance. Hence, the replacements of these components is not so easy which affect the overall production and MRO costs due to down time, rental cost of crane and replacement cost. In this way, the servicing of offshore wind turbine become more expensive as compared to onshore wind turbine (Cevasco et al., 2021; Kotzalas & Doll, 2010; Pinar Pérez et al., 2013).

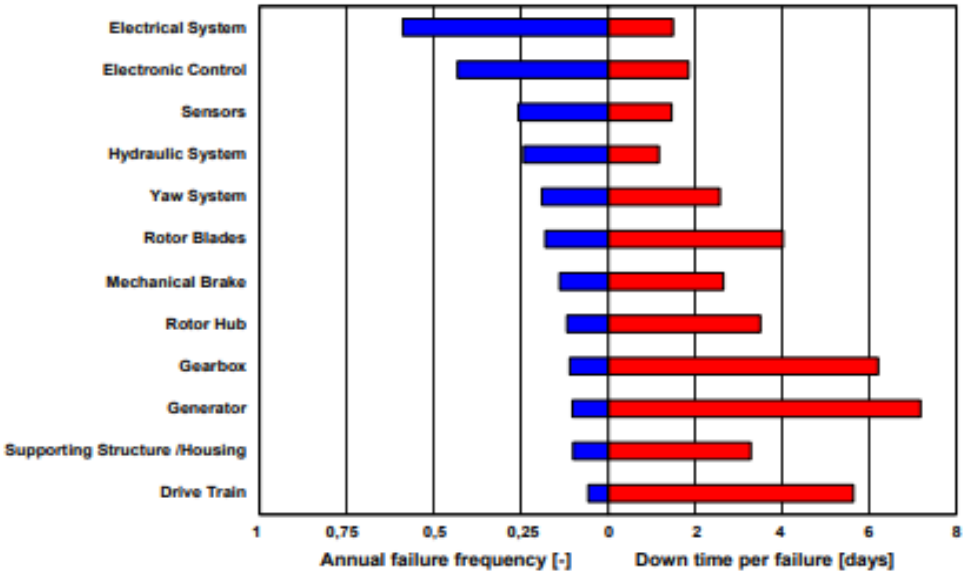

Figure 1. Failure frequency and downtimes of components (Hahn et al., 2007).

1.1. Wind Turbine

Wind turbine converts the kinetic energy of wind into electrical energy and can be classified into two categories mainly on the basis of axis of rotation of the rotor shaft as horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). Due to higher power output and better efficiencies, HAWT are generally preferred over VAWT (Konstantinidis & Botsaris, 2016; McKenna et al., 2016). The basic components of a traditional HAWT have been shown in Figure 2.

The wind strikes on the blades which are attached to the rotor hub and the kinetic energy of the wind gets converted into mechanical energy due to the rotation of the rotor shaft. A pitch-bearing arrangement is made at the rotor hub to adjust the angle of the rotor blades as per wind direction. The rotor shaft (main shaft or low-speed shaft) connects the rotor hub to the gearbox. The gearbox converts the low speed of the main shaft into high speed which runs the generator for electric power generation. The generator is connected to a grid for further electric supply. The main shaft, gearbox, generator and electric controller are fitted in a housing called nacelle at the top of the tower with the help of a yaw system. Anemometer and wind vane are used to control the pitch bearing and yaw system with the help of electric control (EL-Shimy, 2010).

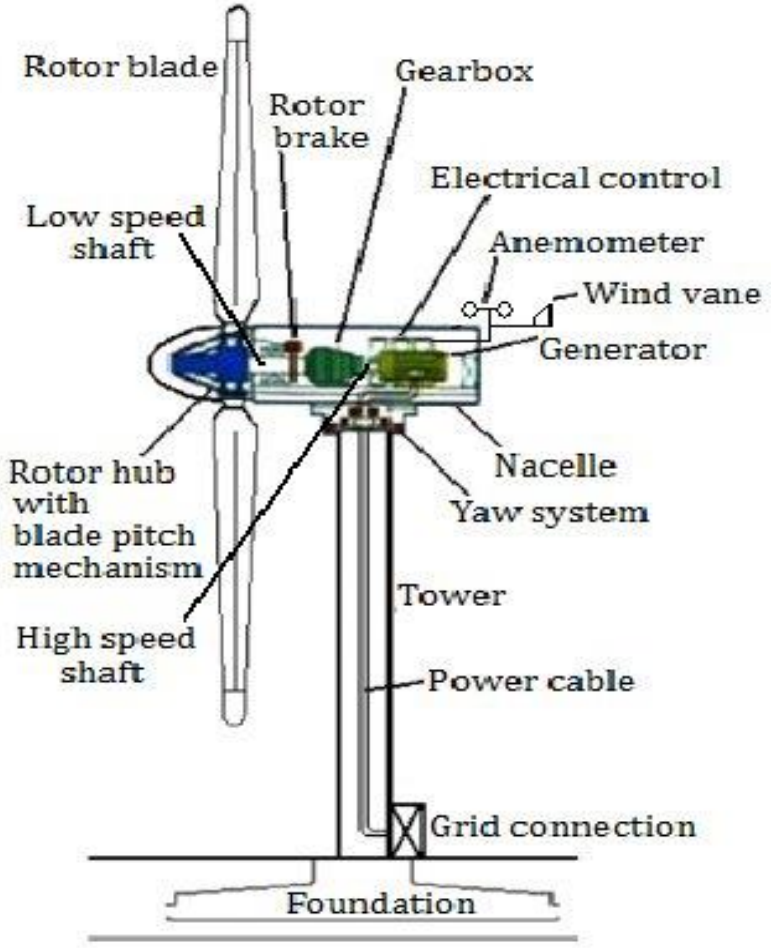

Figure 2. The basic components of a traditional HAWT (EL-Shimy, 2010).

1.2. Gearbox Bearing

Gearbox converts the low speed (10-30 rpm) of the main shaft to high speed (1200-1800 rpm) of the high speed shaft (HSS). The major components of a three stage planetary wind turbine gearbox are input shaft, planet gear, low speed shaft (LSS), intermediate shaft (IMS), HSS and bearings as shown in Figure 3 (Keller et al., 2016). The wind turbine gearbox is designed as per design standard IEC 61400-4 and AGMA 6006.

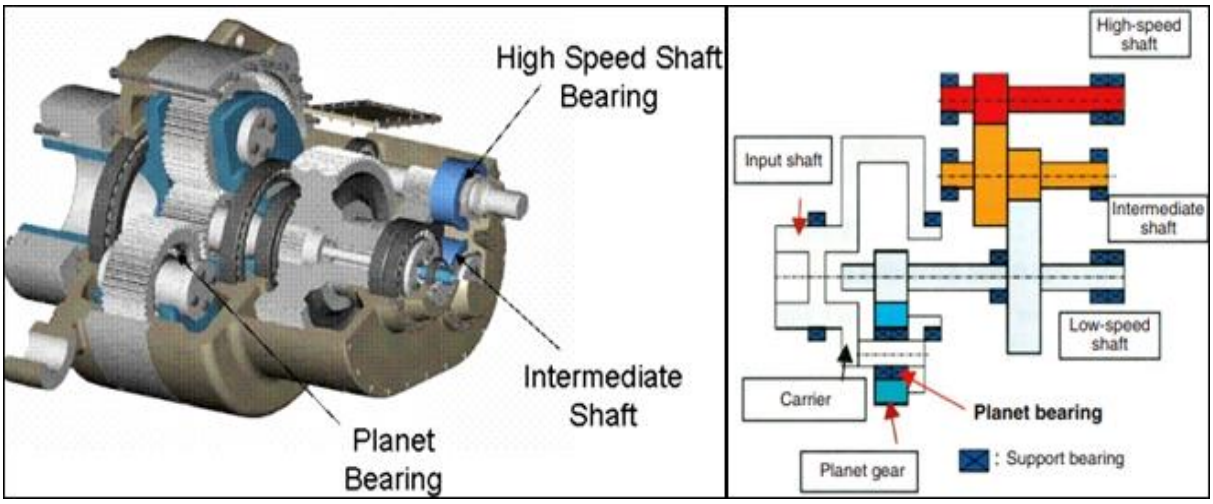

Figure 3. Gearbox (Keller et al., 2016).

In a gearbox, different bearings are used at different locations (main shaft, gearbox, pitch, yaw and generator system) as per their capability to function for an expected life of around 20 years. But the frequent occurrence of premature failure of bearing did not allow to work for the expected life. These bearings are designed as per standard ISO 281, ISO/TS 16281 and generally selected on the basis of dynamic and static load ratings. Rolling element bearings used at various locations in a gearbox have been presented in Table 1.

Table 1 Bearing type for gearbox (Burton et al., 2011).

Area	Side	Bearing types	Maximum contact stress (MPa)
HSS	Fixed	SARB, CRB, TRB, DGBB, 4PCBB	1300
	Free	SARB, CRB, DGBB	
IMS	Fixed	SARB, CRB, TRB, 4PCBB	1650
	Free	SARB, CRB	
LSS	Fixed	SARB, TRB	1650
	Free	SARB, FCCRB	
Planetary Shaft	---	SARB, CRB, FCCRB	1450
Carrier	---	FCCRB, SARB, TRB	Not specified

SARB: Self-Aligning Roller Bearing, CRB: Cylindrical Roller Bearing, FCCRB: Full Complement Cylindrical Roller Bearing, TRB: Tapered Roller Bearing, DGBB: Deep Groove Ball Bearing, 4PCBB: Four Point Contact Ball Bearing.

HSS bearings have higher failure rate because of higher axial force and low contact angle. It has been observed on the basis of field experience that, about 70% of gearboxes failure happens due to bearings, out of which HSS bearings are the major cause of gearbox failure (about 48%) as shown in Figure 4. The maintenance and repairing of HSS bearings cover 50% of the MRO cost (Sheng et al., 2013).

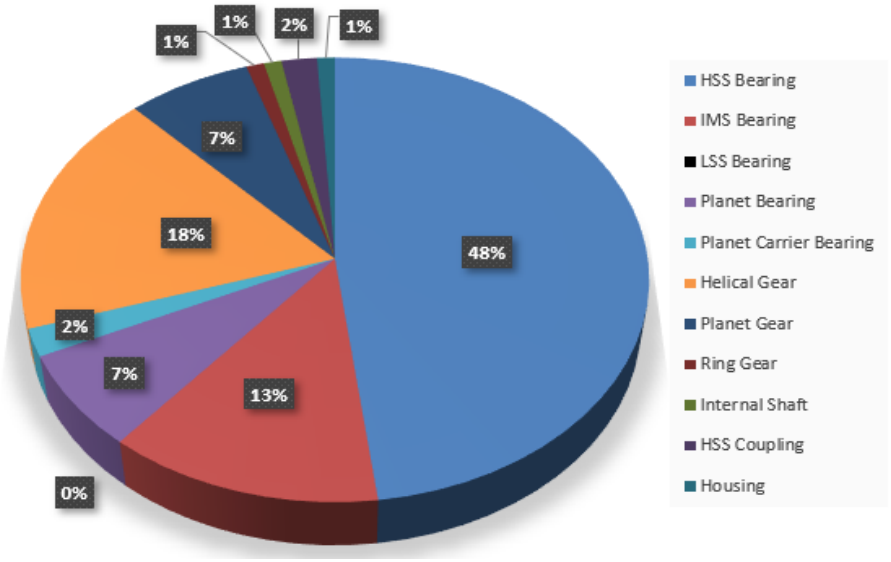

Figure 4. Percentage of failure in the main parts of gearbox (Keller et al., 2016; Sheng et al., 2013).

The variable working conditions such as sudden brake and grid drops, transient wind speed and direction, environmental conditions, fluctuating wind loads etc. are the major reasons of premature failure of wind turbine gearboxes (De Azevedo et al., 2016; Kusiak & Verma, 2012). These conditions can cause scuffing, micro-pitting, white etching cracks (WECs), fretting corrosion etc. on bearing surface which results in premature failure of wind turbine gearbox. WECs on bearing surface is most common failure in wind turbine gearbox (Bruce et al., 2015; Evans, 2016; Greco et al., 2013; Robert et al., 2013).

Generally rolling element bearings perform in two types of load zones i.e., loaded and unloaded zone. Rollers contain high traction forces and are adjusted in regular manner in case of loaded zones whereas, the things are opposite under unloaded zones. Variant wind conditions may cause torque reversals for thousands of times per year. Loading zone of bearings get affected due to torque reversals which results in high contact stresses in rolling element bearings.

Hydrodynamic journal bearing can be a possible solution to reduce the intensity of these high contact stress (Wang, 2013). The applicability of hydrodynamic journal bearings for rotor and planetary shaft have been studied due to various advantages such as lower cost, higher torque density, greater design life, less weight, low noise and vibration as compare to conventional rolling element bearing (Guerenbourg et al., 2012; Rolink et al., 2020).

Hydrodynamic journal bearing carries the load on a thin layer of lubricant. Higher starting torques are required to attain the fully developed lubrication film. These high torque requirements can be reduced by adding a high pressure lubrication system (Hori, 2006).

Now, an interesting question arises here that why hydrodynamic journal bearings are not yet implemented on HSS of the wind turbines.

In comparison to other typical applications of hydrodynamic bearings such as in turbines and compressors, engine and power trains, the operating conditions of wind turbines are very different and most challenging (Han et al., 2017):

- Higher gravitational load
- Variable wind velocity
- Uncontrolled environmental conditions
- Sudden break
- Grid drop

It is observed that all the typical hydrodynamic journal bearings implementations work either one or two of the above stated operating conditions, but in case of wind turbine, all the above mentioned operating conditions act simultaneously which increases the complexity of the design and development (Nosonovsky & Bhushan, 2012).

In the present work, a numerical multi-physics bearing model will be developed for better prediction of performance characteristics of a hydrodynamic bearing under the realistic conditions existing in a wind turbine. The simulation will be performed by solving modified Reynolds equation for angular misalignment and balancing energy and heat conduction equations for thermo-viscous effects. In this way, a thermo-hydrodynamic (THD) model will be developed for static and dynamic responses under steady and transient operating conditions.

Finally, the goal of this research is to explore the possibilities of using hydrodynamic journal bearing for high speed shaft of wind turbine gearbox and its effect on MRO cost. It would present a strong alternative to current state of the art.

2. Literature Review

Premature failures of bearings are the major cause of gearbox failure in wind turbine. In this section, key challenges faced by the gearbox bearings have been discussed.

2.1. Review of Roller Bearings in Wind Turbine Gearbox

Musial et al. (2007) developed a three step approach (dynamometer testing, field testing and drivetrain analysis) to identify the shortcomings involved in the design process of wind turbine gearbox and provide solutions that improved gearbox reliability. Blau et al. (2010) observed the surface damage and wear on failed spherical and cylindrical roller bearing surfaces of high speed shaft (HSS) in wind turbine gearbox. Spherical roller bearing surface shows more evident wear like pitting, spalling etc. due to axial over loading. Surface materials and their treatments and lubricants need to be considered to improve the gearbox design. Greco et al. (2011) investigated the effect of surface treatments (case carburized and electrochemical boriding) and lubricant additives (nano-colloidal boron nitride) on the tribological properties of steel (AISI 9310). The application of electrochemical boriding resulted in hardened gear steel surface and a wear resistant film was observed over the steel surface by using additive lubricant. Sankar et al. (2012) investigated the cause of premature

failure (fatigue fracture) of intermediate shaft pinion and cylindrical roller bearing at non drive end. It was found that that major causes of failure were debris resulted from wear (scoring and spalling) of roller and races and overloading at the time of peak power generations. Greco et al. (2013) analysed randomly selected four different rolling segments two materials (hardened and case hardened steel) and two roller types (CRB and TRB) in which one taper roller bearing of case carburised steel operated under low speed conditions (~10-15 rpm) and three working under high speed conditions (~1600 rpm). Axial surface cracks with white etching areas were observed in all the bearings operated under high speed conditions. Whereas, only micro cracks with high density white etching area were reported for the LSS. Igba et al. (2015) used the available literature related to failure data of a gearbox for the estimation of optimal preventive maintenance time period to reduce downtime and maintenance cost. Age related failures were reported to be more suitable for this type of maintenance. Gallego-Calderon et al. (2015) analysed a three stage (one planetary and two parallel stages) gearbox with cylindrical and tapered roller bearing configurations at planetary stage. The values of reliability index and probability of failure were found to be 3.83 and 3.97; and 9×10^{-5} and 6×10^{-5} for cylindrical and tapered roller bearing configurations, respectively. Gould et al. (2016) analyse four samples taken from the inner ring of a CRB applied over a HSS of gearbox using high energy X-ray tomography. Small cracks were observed around the inclusions. Gallego-Calderon et al. (2017) investigated four-row and single-row cylindrical roller bearings of a planetary shaft to understand the effect of extremes events like normal and emergency stop etc. It was reported that the emergency stop show the more failure on bearings as compared to other events. Future research on implementing breaking methods and techniques had been suggested. Gong et al. (2017) analysed a 3 stage wind turbine gearbox of capacity 1.5 MW for the observation of abnormal wear at inner surface and cylindrical roller of a failed roller bearing. It was observed that the major causes of these wear were the third body abrasive particles resulted from the gear tooth breakage and softer inner ring material. Guo and Keller (2018) investigated the effect of different load conditions applied on the high-speed shaft bearings (taper roller bearings) in wind turbine gearboxes using multibody computer simulation and dynamometer testing. It was reported that the torque reversal resulting from grid loss changes the bearing load zones which cause roller sliding and white etching areas. Paladugu et al. (2018) observed three lubricants (mineral oil: ISO VG68, White etching cracks critical oil: SAE 75W-80 and mineral oil contains 10% water) to check performance of a CRB (thrust bearing) under 60 kN load, rotation of 750 rpm and test rig temp. of 100℃. The mineral oil showed the maximum life (980 hours) followed by mineral oil with 10% water (450 hours) and white etching cracks critical oil (40 hours). Al-Tameemi et al. (2018) studied the effect of debonding at non-metallic inclusions on the surface of a failed CRB of the planetary gear shaft. Butterfly cracks were observed between WEAs and at the tip of inclusion. Wasilczuk et al. (2018) analysed wear patterns of a 1.5 MW HSS bearings of wind turbine gearbox. Smearing and adhesion due to sliding and rolling elements were the root cause of bearing failure. Preloaded downwind bearings with different widths were recommended for reducing the chances of premature failure. Dhanola and Garg (2020) reviewed about tribological challenge experienced by the rolling element bearings of wind turbine. Gearbox bearings were reported to be the major concern as compare to other

bearings for premature failures. Hydrodynamic journal bearings were recommended as the replacement of rolling element bearings due to lesser maintenance and design space, high damping effects and greater integration flexibility.

2.2. Review of Hydrodynamic Journal Bearings in Wind Turbine

The conventional rolling element bearing used in wind turbine have number of problems as discussed in above literature section. Nowadays, hydrodynamic journal bearings are a relatively new solution to enhance the reliability and performance of wind turbine gearbox. In this section we have reviewed the literature of hydrodynamic journal bearings for wind turbine application.

Guerenbourg et al. (2012) designed a fluid pad bearing for the wind turbine main shaft. Generally, due to the adverse operating condition like low-speed, high load and frequent startup and shutdown, the fluid bearing is not used as main shaft bearing. But invented bearing is less susceptible to bearing failure than roller bearing and easily removable or inserted without disassembling the drivetrain. In invented fluid pad bearing numerous additional modifications and variations are done to overcome other issues like wear at startup and shutdown conditions, dynamic load, thrust load, shaft deflection. Meyer (2017) investigated performance of wind turbine gearboxes using journal bearing. Initially, journal bearing test rig and gearbox test rig were used for conducting experiments. No cracks and wear were observed at extreme operating conditions like full load, part load, idling and emergency breaking. To obtaining successful data, gearbox using journal bearing was fitted in nacelle of 2 MW wind turbine. Outcomes showed that the gearbox using journal bearing performed without any flaw or wear and less noise and vibration. Schroder et al. (2019) presented an innovative design of conical sliding bearing for main shaft bearings of wind turbines. Performance characteristics of the design were evaluated under mixed lubrication regime. Slightly smooth surfaces were observed for pads under high load zones during the disassembly of tested bearing. Rolink et al. (2020) studied the double conical pad bearing for rotor shaft of wind turbine. Result reviled that both side pad segment shows parallel displacement under edge loading but due to thrust loading all rear cone pad (gearbox side) worked under loaded zone which was cause of elastic deformation of rear cone pad. Asymmetrical bearing pad with high inclination angle of the rear cone can be a future aspect for better load distribution. Hagemann et al. (2021a) analysed the static performance characteristics of sliding bearing for planet gear shaft of wind turbine using thermo-hydrodynamic model. It was reported that an increase in the helix angle of planetary gear, increases the external moment which further increase the edge loading and may cause wear. Hagemann et al. (2021b) also studied the impact of structure deformation on the operating behavior of sliding bearing for planet gear shaft of wind turbine. The deformation in planet and carrier pin instigate the lower film thickness at highly loaded region in bearing.

3. Research Gap

In available literature, most of the researchers have discussed the cause of gearbox bearings failure and also suggested some modification in design of existing rolling element bearing to address various issues. Some of the researchers have also checked the applicability of hydrodynamic journal bearing for main shaft (rotor shaft) and planetary gear shaft of gearbox but there is no investigation on application of hydrodynamic journal bearing for high speed shaft of wind turbine gearbox. However, theoretical analysis of misaligned hydrodynamic journal bearing for high speed shaft of wind turbine gearbox considering the thermo-viscous effect under steady and transient condition is not reported in literature yet. To the best of author's knowledge, no investigation is available that deals with design and numerical analysis of static and dynamic performance of misaligned hydrodynamic journal bearing under steady and transient states for high speed shaft of gearbox in wind turbine.

4. Problem Definition

The problem considered for this proposed research work is the analysis of hydrodynamic journal bearing for high speed shaft of wind turbine gearbox.

4.1. Objectives

The present study aims to explore the possibilities of replacing the existing rolling element bearing on high speed shaft of wind turbine gearbox with a hydrodynamic journal bearing in order to increase the performance and reliability of gearbox. This study would be evaluated on the basis of numerical modelling to fulfill the following objectives.

- Numerical modelling and analysis of existing rolling element bearings for high speed shaft of wind turbine gearbox considering elasto-hydrodynamic lubrication.
- Numerical modelling of a misaligned hydrodynamic journal bearing for high speed shaft of wind turbine gearbox under steady and transient state conditions considering thermo-viscous effect.
- To study the static and dynamic performance characteristics of hydrodynamic journal bearing for high speed shaft of wind turbine gearbox.
- To compare the performance characteristics of hydrodynamic journal bearing with existing rolling element bearing for high speed shaft of wind turbine gearbox.

4.2. Methodology

The present research work will be completed in two phases for which a tentative methodology has been given below:

In the first phase, rolling element bearing will be analyzed for high speed shaft (HSS) of wind turbine gearbox by using classical theory or FEM to compute static and dynamic performance characteristics. To consider the elastic deformation and piezo-viscous effect due to high contact pressure, film thickness and Reynolds equation will be modified respectively for rolling element bearing. This analysis will be based on Elasto-hydrodynamic (EHD) theory.

In a similar way, detailed literature survey will be conducted to narrow down the selection of design parameter of hydrodynamic journal bearing for HSS of wind turbine gearbox. To consider the thermo-viscous effect in the misaligned journal bearing under transient and dynamic conditions, modified Reynolds equation, 3D Energy equation and 3D Heat conduction equations will be solved simultaneously using numerical method (FEM/FDM). Various steps involved in the solution procedure have been shown in Figure 5 and described below:

1. Initially start the programme using input data like aspect ratio (L/D=0.5-1.5), eccentricity ratio (ε=0.1-0.9), attitude angle (ϕ), degree of misalignment (D_m), angle of misalignment (ϕ_m) etc.
2. The initial value of pressure and temperature will be selected to start the programme.
3. Film thickness and viscosity functions will be calculated for the selected input value.
4. Modified Reynolds equation will be solved to compute the pressure.
5. The calculated pressure will be used to compute velocities and their gradients required for solving 3D energy equation for fluid-film temperature. Fluid-film temperature and journal temperature changes continuously as per boundary conditions and iteration will be terminated when journal temperature converge.
6. At the same time bush temperature will be computed using 3D heat conduction equation. At the fluid-bush interface fluid-film temperature and bush temperature changes continuously as per boundary conditions and iteration will be terminate when bush temperature converge.
7. After the convergence of journal and bush temperature, nodal fluid film temperature will be used to modify the viscosity of fluid. This modified viscosity will be used to compute new film pressure from step-2. The procedure will be repeated till the complete convergence of pressure, temperature achieved.
8. Final result will be computed in the form of static and dynamic performance characteristics of hydrodynamic journal bearing for high speed shaft of wind turbine gearbox.

In the second phase, the performance characteristics of hydrodynamic journal bearing and existing rolling element bearing for high speed shaft of wind turbine gearbox will be compared.

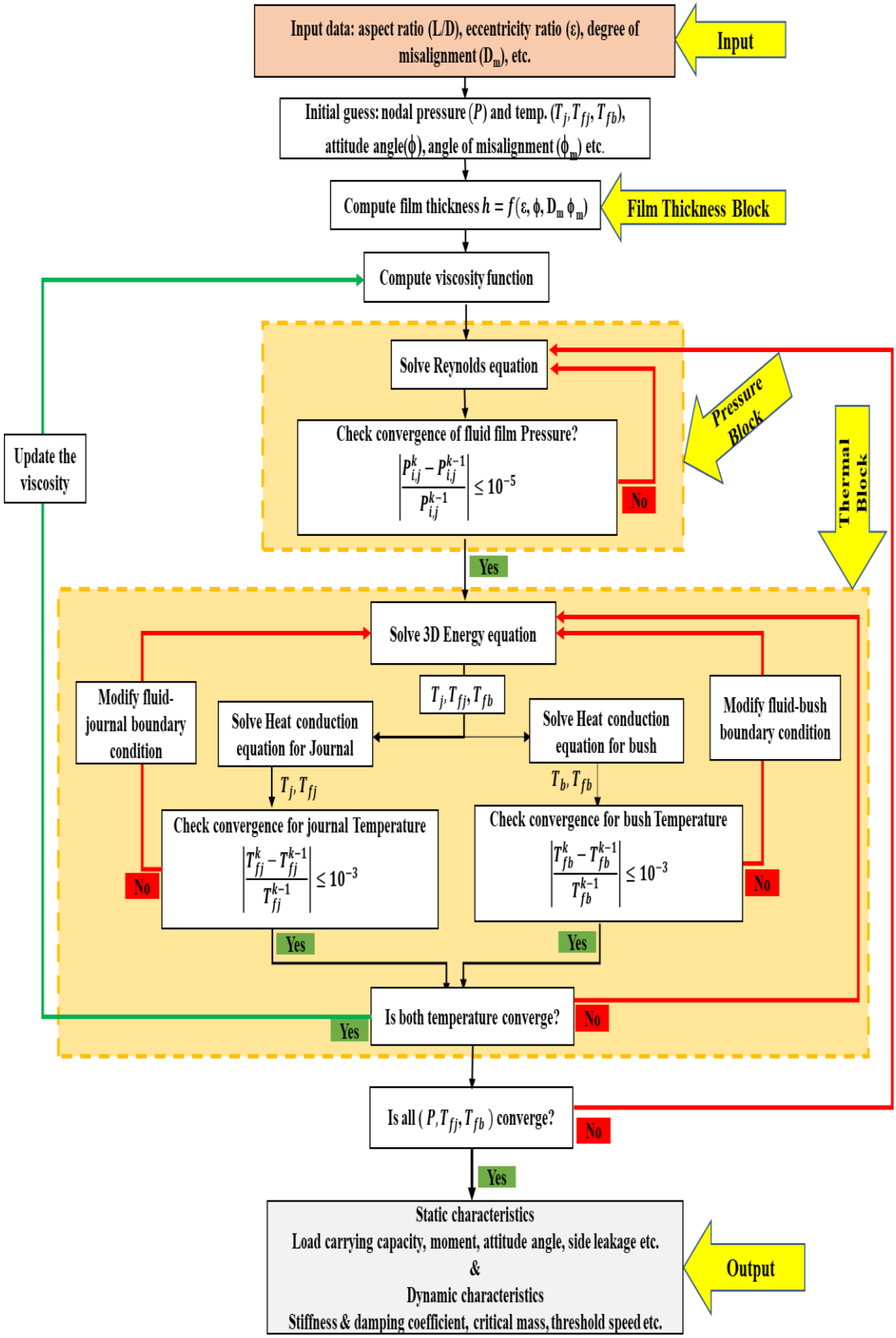

Figure 5. Flow chart.

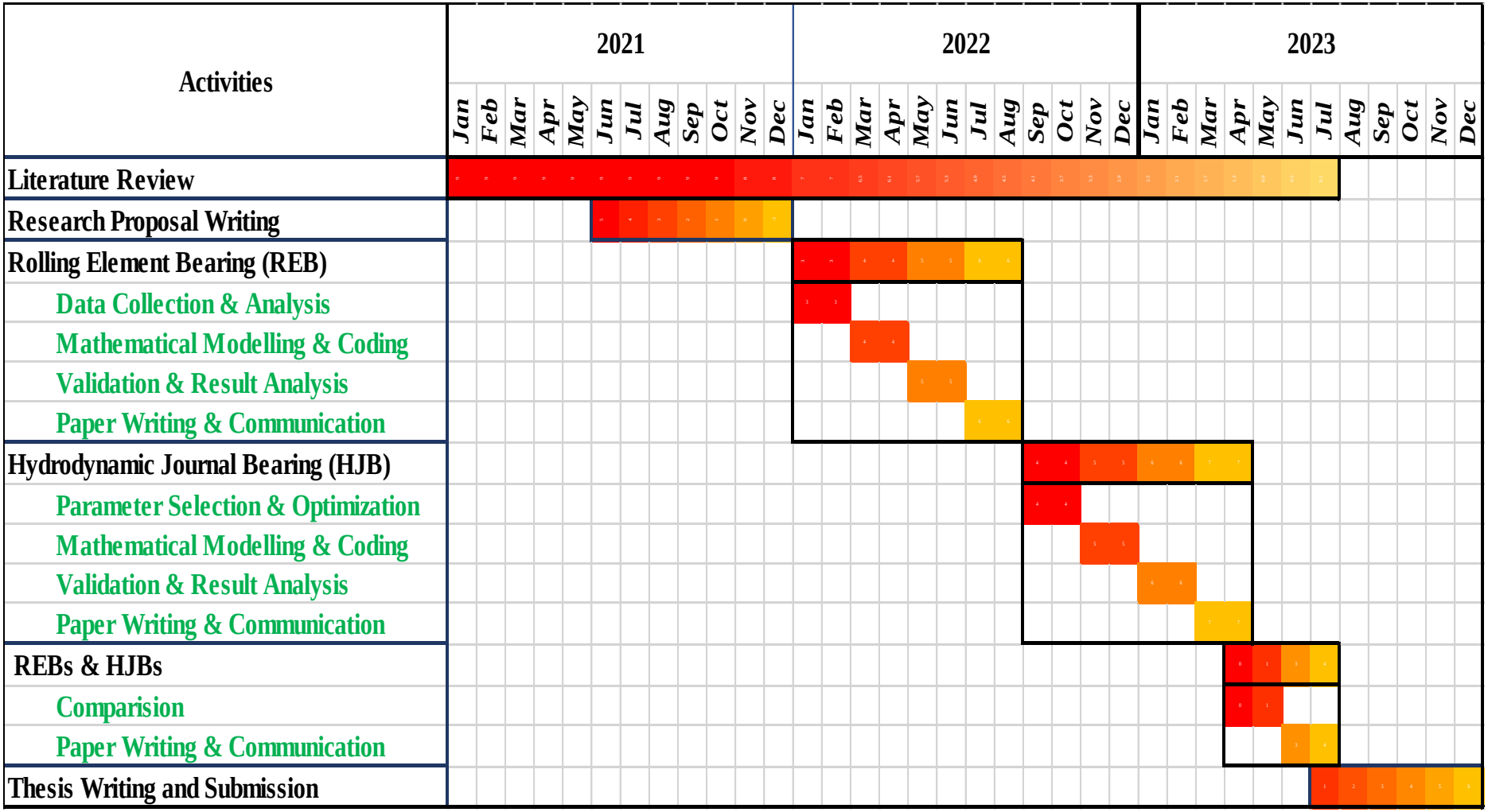

Figure 6. Ph.D. Gantt Chart

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